Improvement of thunderstorm hazard information for pilots through a ground based weather information and management system

The CB WIMS approach in FLYSAFE

A. Tafferner and C. Forster
Institut für Physik der Atmosphäre
Deutsches Zentrum für Luft- und Raumfahrt
Oberpfaffenhofen, Germany
arnold.tafferner@dlr.de

S. Sénési and Y. Guillou
Prévision Immédiate
Météo-France
Toulouse, France
stephane.senesi@meteo.fr

***Abstract*—The development and outcome from first evaluations of the thunderstorm weather information management system 'CB WIMS' in the EU project FLYSAFE is described. Preliminary results from a flight test campaign carried out in summer 2008 involving two research aircraft are presented. They lead to the conclusion that information about thunderstorm hazards delivered from CB WIMS through a ground based weather processor and satellite communication to an aircraft could help to improve the pilot's awareness of the weather situation and assist in flight planning particularly in complex thunderstorm situations where the on-board radar cannot provide the pilot with the full situation awareness due to scanning geometry and radar beam attenuation.**

Keywords - FLYSAFE; weather hazard; cockpit weather information; thunderstorm; NG-ISS; flight test

I. Introduction

In the perspective of a trebling of the flights over the period 2000-2020, the preservation of a high level of safety was retained as a priority research axis by the European Commission and ACARE (Advisory Council for Aeronautics Research in Europe). An important piece of this research has been put in place early in 2005: the FLYSAFE Project (http://www.eu-flysafe.org/). It is a European Commission funded project aiming at improving flight safety through the development of a Next Generation Integrated Surveillance System (NG-ISS). The NG-ISS provides information to the pilot on a number of external hazards which address the three types of threats:

- traffic collision
- ground collision
- adverse weather conditions

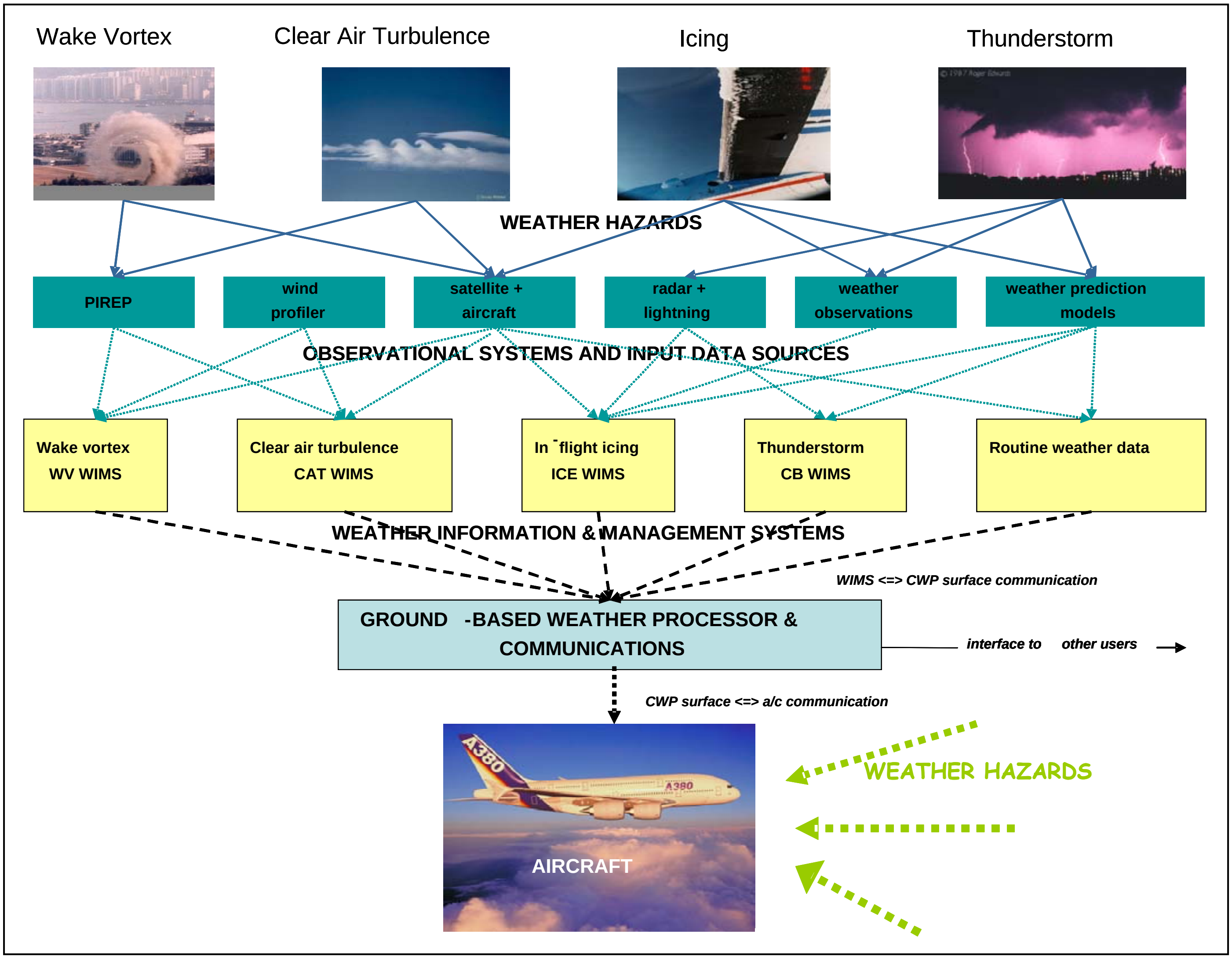
Also, FLYSAFE developed new systems and functions for:

- improved situation awareness
- advanced warning
- alert prioritization
- enhanced human-machine interface

One particularly innovative feature of the NG-ISS is that it is coupled to ground facilities which are being designed to provide the best possible nowcast (short range forecast up to an hour) of the most dangerous meteorological hazards. This is made possible by the development of so-called Weather Information Management Systems (WIMSs). The WIMSs are best thought of as expert systems which bring together all available information about the hazard under consideration and provide an optimised nowcast for aircraft at risk (Fig. 1). Individual WIMS have been developed for the weather hazards icing (ICE WIMS), clear air turbulence (CAT WIMS), wake vortex turbulence (VW WIMS) and thunderstorms (CB WIMS; Cb = Cumulonimbus). These systems provide meteorological data on the individual weather hazards over defined areas ranging from high resolution local scale over continental to global scale.

All WIMS data are sent to a ground based weather processor (GWP). By request from an aircraft selected information about a weather hazard tailored to a respective flight corridor is passed through the GWP to the on-board NG-ISS where a fusion not only with on-board weather data, but also with the other threats terrain and traffic is carried out in order to achieve a consolidated picture of the hazard situation. Finally, the situation is presented to the pilot by means of simple, easy to read graphics on a special display together with the possible solution on how to avoid the hazard.

The CB WIMS has been developed with involvement of partners from the German Aerospace Center (DLR), Météo-France (FMET), ONERA (Paris), the UK Met-Office and the University of Hannover. This paper describes the implementation of the Cb WIMS, the evaluation strategy, and preliminary results which can be deduced from the flight tests.



F igure 1. Weather hazards treated in FLYSAFE in Weather Inforamation Management Systems (WIMS) and communication to the aircraft

II. THE CB WIMS APPROACH

In order to be useable by pilots or fused with other on-board weather data the information provided by a weather information system must be simple, easy to understand, of small storage size and quickly deliverable in real time. This stands in contrast to the complexity of weather features like thunderstorms which appear in various shapes and sizes and corresponding life times from a few tens of minutes to several hours. The problem of how to reduce this complexity to certain 'hazard volumes' for air traffic which are tractable and communicable to users has been discussed in [9]. The strategy followed in the development of CB WIMS was not to describe thunderstorms to any observable detail, but to identify the hazards for aircraft in thunderstorm situations, to find corresponding thresholds for the specific hazard levels "moderate" and "severe", where severe indicates a no-go volume of air space, and based on these, to define hazard objects which represent these hazard levels. The task of CB WIMS is therefore to detect and forecast these hazard objects on the very short term, e.g. for up to one hour in advance.

0renders a schematic depiction of such thunderstorm hazard objects (re-drawn from [9]). The various threats an aircraft is exposed to when flying into a thunderstorm, e.g. during flight phases landing and take-off or en-route, are indicated in the figure. The volumes have been given the names Cb top and Cb bottom. In addition, volumes may be nested due to the prescription of two levels of severity. As will be shown later the volumes are not cylinders as depicted here, but are polygon surfaces with bottom and top

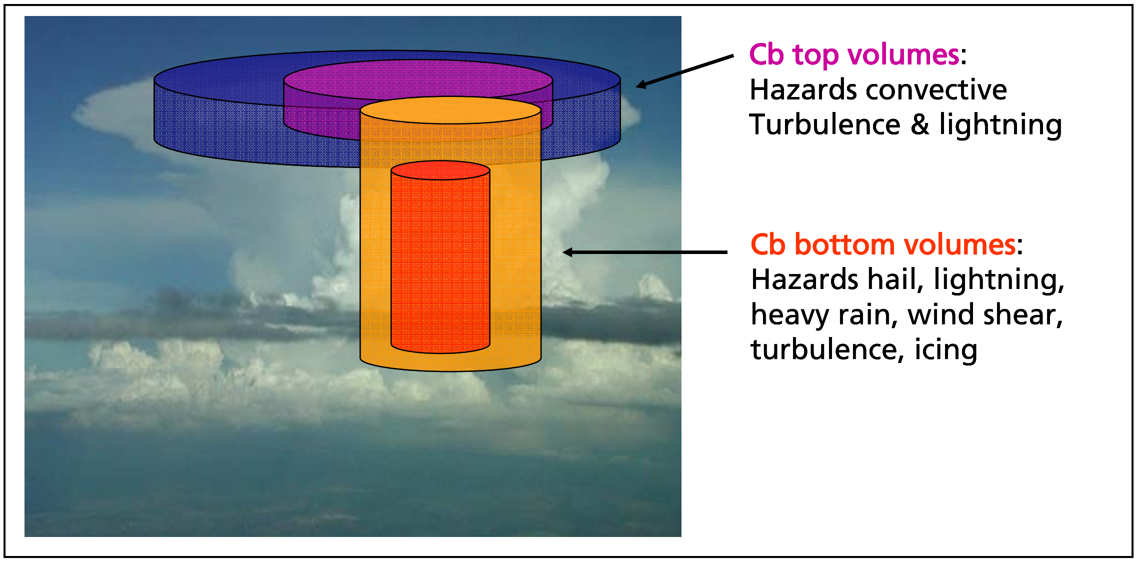


Figure 2. Thunderstorm (Cb) weather object rendered as idealized volumes (redrawn from [9]).

III. CB WIMS DEVELOPMENT AND FEATURES

The role of the various partners involved in the development of CB WIMS is detailed in [9]. However, for quick reference and in order to ease understanding in what follows in the evaluation (paragraph V and VI) the main parts of development and features of Cb WIMS shall be listed here briefly.

Based on meteorological input data, including remote sensing observations and numerical model data, the CB WIMS provides thunderstorm information on three different scales, i.e. areas. The different scale products developed and provided by the CB WIMS partners are as follows.

- Local or TMA scale, where TMA stands for Terminal Manoeuvring Area of an airport, derived from systems developed at Météo-France, DLR and ONERA
- Continental scale derived from systems developed at Météo-France, DLR and ONERA
- Global scale provided by the UKMET-Office' global forecast model

These scale products differ not only in terms of area covered, but also in spatial resolution and time between updates. For the evaluations however (paragraph V, VI) only the local and continental scales are considered. The continental product covers an area such as that of Central Europe, while the local (TMA) product is limited to roughly 300 km around an airport (Paris Charles de Gaulle in this case). These products are generated independently by the partners and delivered to the ground based weather processor (GWP) in the form of thunderstorm bottom and top volumes.

For providing bottom volumes Météo-France has set up a real-time processing of 3-dimensional radar data for five radars surrounding the Paris TMA. This processing suite has been implemented at a refresh rate of 15 minutes and with corresponding spatial resolutions of 2 km in the horizontal and 500m in the vertical. Technically, the 3D fields are computed following [2] , using a concept developed several years ago [3] in a research context and now applied in an operational environment. A downscaling technique has also been implemented in order to reach the required 1 km² x 5 minutes space-time resolution over the central part of the TMA by taking advantage of the frequent low elevation scans. The 3D data is used in the CONO software [5] for better defining the

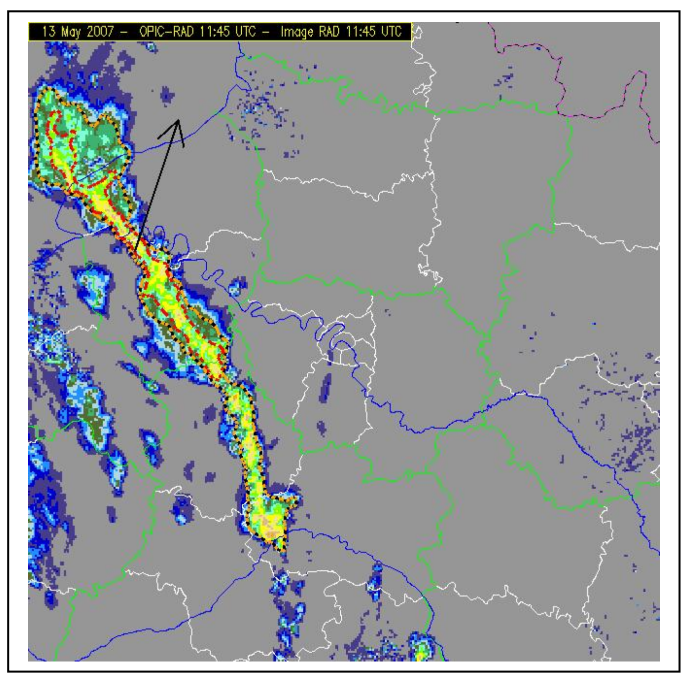


Figure 3. Cb bottom contours marked in colors of orange for hazard "moderate" and red for "severe" overlaid on radar imagery for TMA Paris on 13 May 2007, 1145 UTC. The arrow indicates the forecast moving direction of the bottom object's gravity center.

echo top height and maximum reflectivity of objects. The computation of objects at two severity levels has been implemented, using reflectivity thresholds of 33 and 41 dBZ which were shown to best match the thunderstorm occurrences in METAR reports for towering Cumulus and Cumulonimbus, respectively and are in close agreement with a previous study [8]. 0shows an example of bottom volumes over the TMA Paris for 13th May 2007 1145 UTC. Outlines of volumes over radar reflectivity are given in orange for severity 1 (moderate) and red for severity 2 (severe). Also indicated is the direction of movement of the thunderstorm cells.

For the detection of CB top volumes DLR uses its cloud tracker Cb-TRAM which detects convective clouds in the three stages "initiation", "rapid growth" and "mature" using a special three-channel combination of METEOSAT data. Details of the algorithm can be found in [10]. For delivery to the GWP only volumes containing mature thunderstorm cells are selected, because growing cells have not reached tropopause level (yet) and therefore do not represent thunderstorm tops. CB TRAM is used for both the TMA and regional scales. However, METEOSAT rapid scan data with a refresh rate of 5 minutes are used for the TMA whereas conventional METEOSAT with a refresh rate of 15 minutes are used for the continental scale. Thus, the refresh rates for both Cb bottom and top volumes are the same for TMA and the continental scales. Lightning data from the LINET network [1] are used for CB top volumes to discriminate between severity levels moderate and severe, where 'severe' is used when at least for 50 % of the pixels within the top volume a lightning observation is found next to them within five minutes. Fig. 4 shows an example of detected thunderstorm top volumes at the same time instant as shown for the bottom volumes.

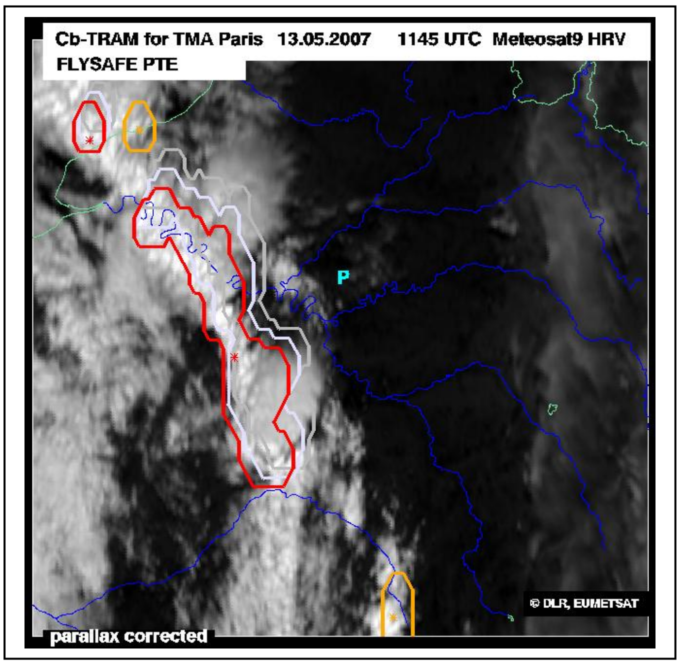


Figure 4. Cb top contours marked in colors of orange for "rapid development" and red for "mature thunderstorm" , overlaid on satellite imagery in the high resolution visible channel. Also marked are nowcast positions after 30 and 60 minutes in white and grey. TMA Paris on 13 May 2007, 1145 UTC

Besides detection and tracking the bottom and top hazard volumes both algorithms provide also nowcasts of future positions and development up to an hour ahead in time. In Fig. 4 the grey contours show the extrapolated positions of the mature cells (in red) after 30 and 60 minutes. Besides location, the Cb objects are provided with a number of attributes. These are:

- Area covered, as a polygon
- confidence level
- hail occurrence flag
- layer (top or bottom)
- moving direction
- moving speed
- gravity centre location
- severity
- trend on area
- trend on vertical development
- upper boundary
- lower boundary

As seen from the list, there appears also a confidence level which expresses the confidence the CB WIMS producer has in the validity of the product. It is a number between 0 and 5 (for lowest and highest confidence, respectively) and is based essentially on the availability of relevant input data to the CB WIMS and on forecast range. In addition to the parameters listed the WIMS's output files contain also a "Status Weather Product" section containing a set of parameters describing mainly the origin and validity of the data available to the CB WIMS. This is the so-called meta-data section. It provides also information on the product scale (local, regional, or global scale) including the coordinates of the coverage area.

IV. REAL TIME OPERATION

The Cb WIMS output is formatted in an advanced XML/GML format which was also developed within the framework of FLYSAFE [6]. This output is transmitted in real time to the GWP from which, after request from the aircraft, the Cb objects are transmitted together with CAT WIMS and ICE WIMS data via satellite link to the on-board NG-ISS. Only those data are transmitted from the GWP which correspond to a specific weather corridor, i.e. an ellipsoidal shaped region that surrounds the aircraft and will be traveled during the next 10 to 60 minutes, depending on flight direction (Fig. 5).

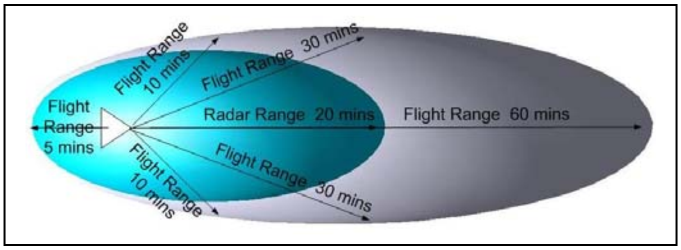


Figure 5. Weather corridor around an aircraft

V. FLYSAFE EVALUATION STRATEGY

Two main task evaluations have been defined in FLYSAFE, i.e. evaluations by a full flight simulator (FFS) located at NLR [4], and flight tests.

A. *Flight simulator tests*

The FFS focuses on the improvement of the WIMS display in the cockpit, on the expected impact on flight safety and on finding out the degree of acceptance of the new information through the pilot. Therefore, the simulator tests have the following evaluation objectives:

- Weather data fusion of onboard radar and WIMS
- Cockpit HMI
- Operational aspects
- Impact on safety

The experimental set-up is sketched in Fig. 6. Thunderstorm situations have been simulated with a numerical weather forecast model from Météo-France. From its output WIMS objects are calculated in the same way as would be done using real data and stored in a local weather processor (LWP). Also synthetic radar data are generated from the model and stored in the on-board data base (ADWR). For comparing on-board weather and WIMS products from the ground, on-board radar images are simulated as would be seen in a flying aircraft and displayed to the pilots. Also weather objects are fused with the simulated on-board radar and shown on display. This set-up enables to test the data flow and the fusion of the objects. It also allows to assess the new cockpit HMI, operational aspects and the expected impact on safety. For more information the reader is referred to [7]. The evaluation of the FFS tests are still going on, final results are expected in the first half of 2009.

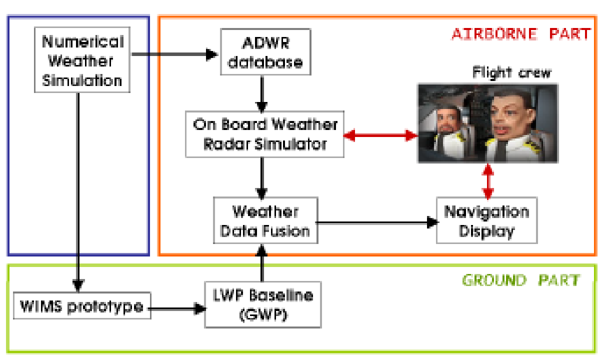


Figure 6. Weather data flow in the NLR Full Flight Simulator

B. *Flight tests*

For the summer period 2008 flight tests were planned involving a ATR-42 research aircraft from SAFIRE and a Metro Swearingen II operated by NLR (Fig. 7). The goals of the flights were:

NLR aircraft:

- To test uplink of WIMS data for CAT, ICE, CB
- To demonstrate real time on-board data fusion of enhanced weather radar data with CB WIMS object data
- To display on-board weather radar data, WIMS data and fusion of both

SAFIRE aircraft:

- Weather of interest: Cb, ICE and CAT
- Video recording of weather radar display
- Offline evaluation of recorded weather parameters and radar display

Flight test have been performed from 6th August till 9th September 2008. Flights have been carried out on about 20 days for both TMA and continental areas. Thunderstorm, ICE and CAT encounters have been reported. The real time uplink of WIMS data, the fusion of weather data onboard and display has been successfully accomplished. The evaluation of the results is still going on (see also next paragraph).

Figure 7. Research aircraft involved in FLYSAFE flight tests. NLR Metro Swearingen II (top) and SAFIRE ATR-42 (bottom).

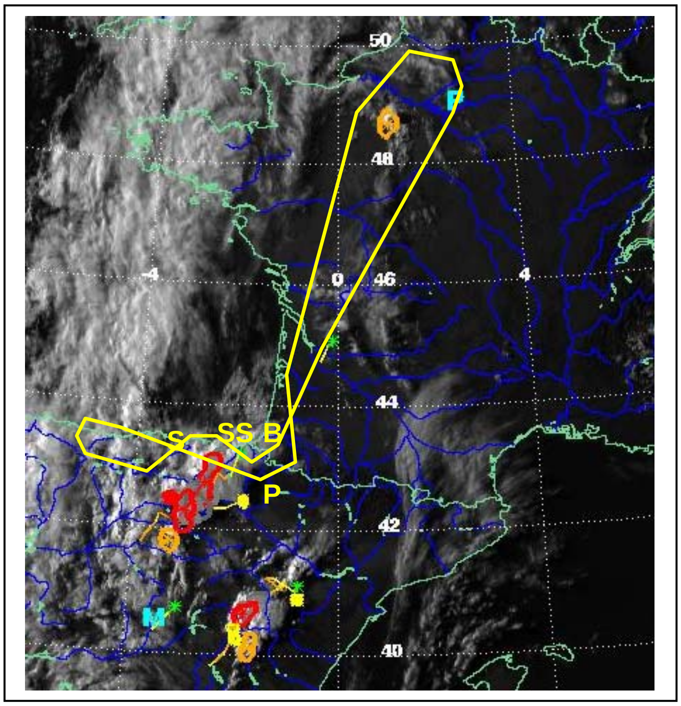


Figure 8. Cb top contours (red) at 1725 UTC, 6[th] August 2008 and flight path of SAFIRE aircraft

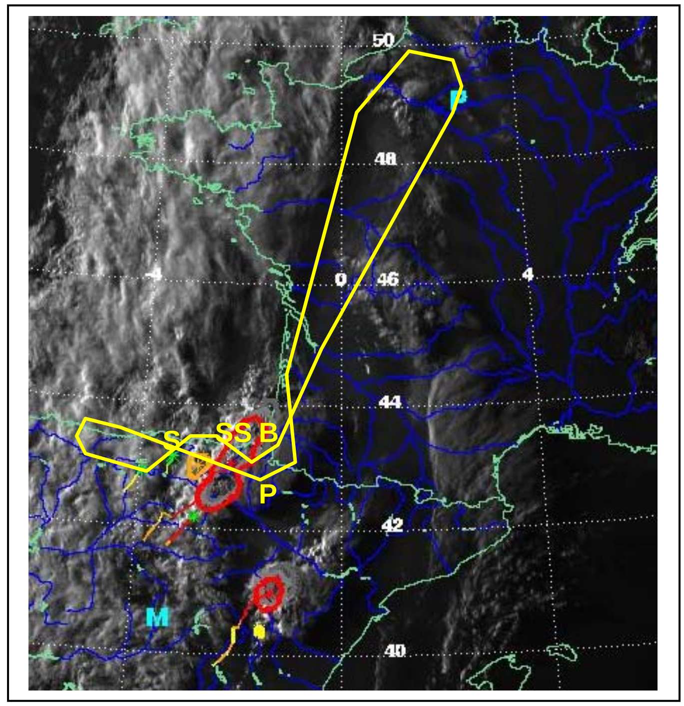


Figure 9. As figure 8, but 1825 UTC

VI. FIRST RESULTS FROM FLIGHT TESTS FOR CB WIMS

A. Comparison of CB WIMS products with flight reports

A first flight took place on 6 August 2008 with the SAFIRE aircraft. Fig. 8 shows the Meteosat high resolution visible image and the Cb top volumes at 1725 UT. Three mature thunderstorm cells are detected over northern Spain (red contours). Also indicated in the figure is the flight path. The aircraft started at 1500 UTC from Pontoise (Paris; blue 'P' in the figure), reached Biarritz (B) at about 1700 UTC, continued north of San Sebastian (SS) to Santander (S) at about 1800 UTC, reached Pamplona (P) at about 1830 UTC and then flew back to Pontoise. Fig. 10 shows CB bottom volumes (red contours) which are found below the CB tops in the same area overlaid on the dedicated European radar composite. At 1725 UTC the crew reported "We are flying below the anvil of the Cb situated at San Sebastian with moderate turbulence". From Fig. 8 one can see that this must have occurred just north of the detected northern Cb cell ('SS' for San Sebastian). Also on the way back the crew noted "Flying back just before the Cb over Santander", and later at 1815 UTC: "Flying between two Cb, moderate turbulence" and at 1821 UTC: "Lightning, severe turbulence". This corresponds to the situation one hour later as compared to Fig. 8, when the Cb top cells have moved northward as correctly nowcast by CB WIMS (grey contours in Fig. 8; arrows in Fig. 10). Fig. 9 shows this situation. The flight track is seen to cross the elongated Cb top cell which has merged from the two previous cells.

This example shows that the thunderstorm cells in northern Spain were correctly detected and nowcast by Cb WIMS. The indicated hazard was indeed encountered in that region and time (severe turbulence, lightning).

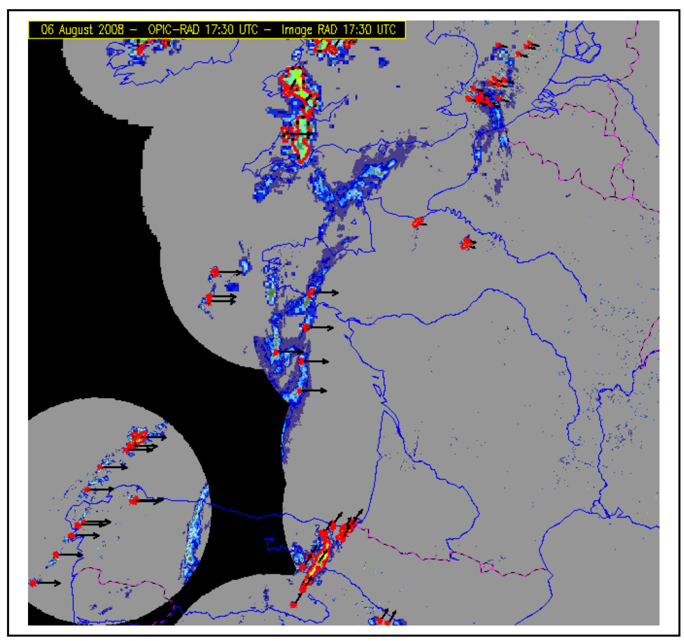


Figure 10. Cb bottom contours (red) and movement as indicated by the arrows overlaid on the dedicated European radar composite at 1730 UTC, 6 August 2008

B. *Comparison of detected CB WIMS objects with onboard radar imagery*

Another flight took place on 19 August 2008 when a cold front moved over France and thunderstorms were generated along the frontal line. Fig. 11 depicts this situation. Cb WIMS detects several Cb top cells (red contours). Also shown are lightning observations in pink which correspond well with the detected cells. The French radar composite indicates the precipitation areas at about the same time (Fig. 12). Also drawn is the flight path in the figure (clockwise from Toulouse). Near La Tour du Pin (small triangle in the figure) the onboard radar was photographed during flight and later overlaid by Cb bottom (Fig. 13) and top contours (Fig. 14) issued by CB WIMS for that time. Despite the poor quality of the radar display picture, one can recognize quite a good match of both bottom and top contours with the detected cell in the onboard radar image. Recall that CB bottom contours are derived from ground based radars and top contours from satellite data. Furthermore, the CB WIMS cells give additional valuable information on the occurrence of convective activity beyond the range of the on-board radar which is confirmed by later on-board radar images. Also they provide information over a wider sector including the area behind the aircraft. This could be valuable in situations when the aircraft has to turn sharp e.g. during take-off and landing procedures. Last not least, CB bottom and top volumes match also very well against each other as is apparent from comparison of the contours in both figures 13 and 14, with the area of the top volume being slightly larger as can be expected from the typical appearance of thunderstorms, i.e. precipitation versus cloud area.

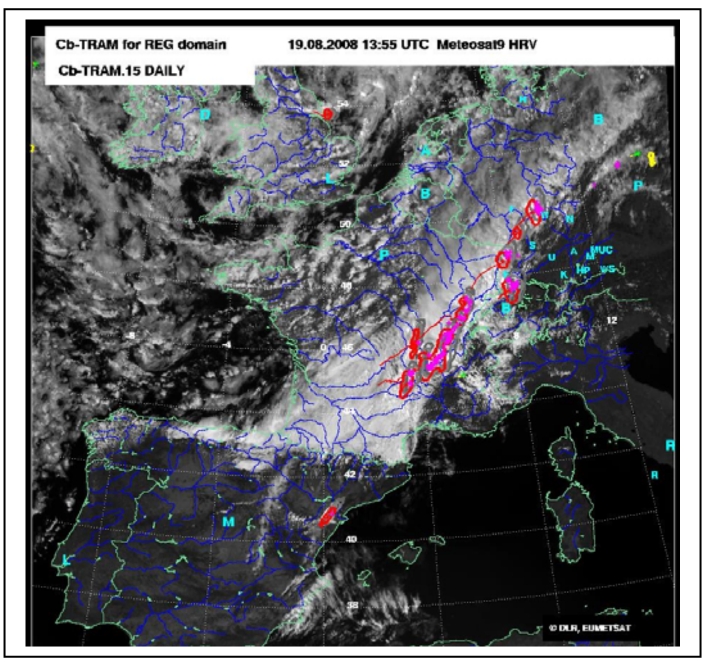


Figure 11. Meteosat image (HRV) and thunderstorm top objects as detected by CB WIMS for 1355 UTC 19th August 2008, Also shown are lightning observations from the LINET network in pink.

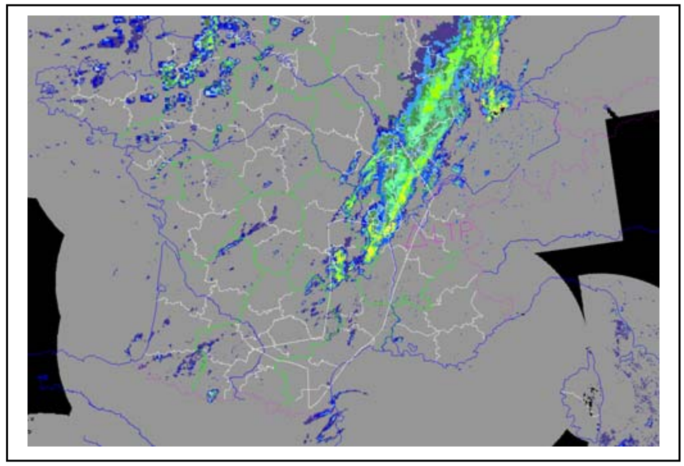


Figure 12. Radar mosaïc at 20080819 at 1405 UTC over central eastern France Flight path (clockwise from Toulouse at cruise level 180). Onboard observations near Lyon, landmark LTP stands for "La Tour du Pin"

Work is going on to systematically produce comparisons like the one presented here also for the other flights. The video camera recordings from onboard the SAFIRE aircraft seem to be of a quality good enough to be used for similar comparisons of onboard radar and CB WIMS products. More results can be expected in the very near future.

VII. CONCLUSIONS

Although the results presented here stem from only two test flights, the apparent accuracy of the WIMS products provides well-sounded hope that the remaining evaluations will confirm these preliminary results. Previous findings [9] can be confirmed in that relatively simple Cb top and bottom volumes derived from METEOSAT and radar data can provide realistic coherent hazard areas for air traffic. However, one should not forget that the production of these CB WIMS objects involves quite complicated algorithms which retrieve the necessary information from raw remote sensing data. Also, these algorithms had to be efficiently coded in order to be robust and processing time fast enough to be run in real time. The ongoing evaluation of the NLR aircraft test flight data where the data uplink to the cockpit has been demonstrated to work will exhibit which is the delay between analysis time of weather features and display time of WIMS products in the cockpit due to data collection, distribution, processing and transmission through the ground weather processor to the cockpit. First estimations from CB WIMS delivery times indicate that objects from CB WIMS can be used for fusion in the cockpit which are forecasts of up to only 15 minutes or less and therefore quite reliable.

Of particular value to the pilot is the additional information about the thunderstorm situation which can be gained by overlaying the Cb WIMS object data with onboard radar data as noted in the previous paragraph. This provides the pilot with a more complete picture of the hazard situation and helps in decision making.

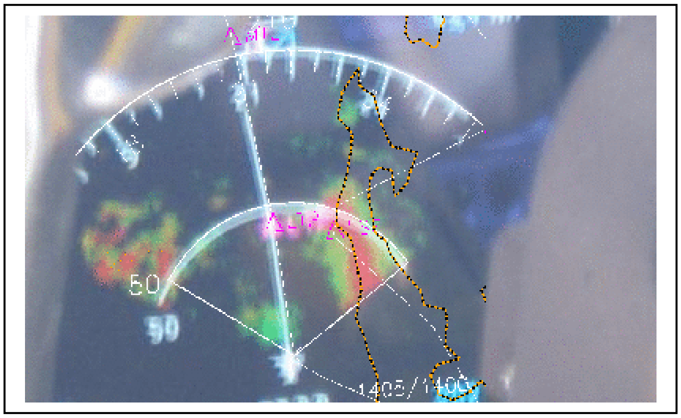
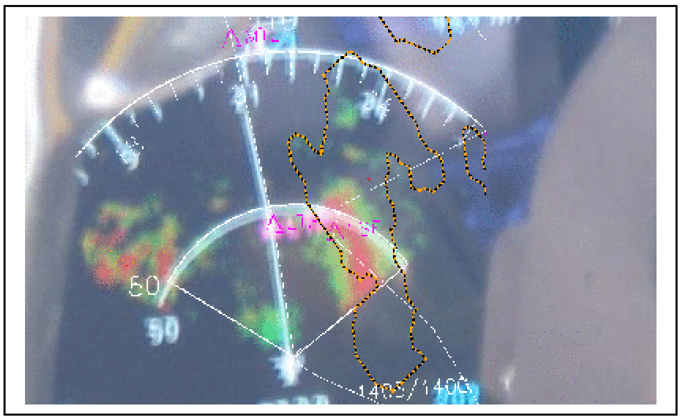


Figure 13. Onboard flight display with radar and Cb bottom contours

Figure 14. As Fig. 13 but overlaid with CB top contours



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REFERENCES

[1] Betz, H.-D., Schmidt, K., Oettinger, W. P., and Wirz, M.:Lightning detection with 3D-discrimination of intracloud and cloud-to-ground discharges, *Geophys. Res. Lett.*, 31, L11108, doi:10.1029/2004GL019821, 2004.

[2] Bousquet, O., P. Tabary and J. Parent-du-Châtelet. On the value of operationally synthesized multiple-Doppler wind fields, Geophysical Research Letters, vol. 34, l22813, doi:10.1029/2007gl030464, 2007.

[3] Bousquet, O. and M. Chong. A Multiple-Doppler Synthesis and Continuity Adjustment Technique (MUSCAT) to Recover Wind Components from Doppler Radar Measurements. *Journal of Atmospheric and Oceanic Technology*, 15, No. 2, pp. 343–359, 1998.

[4] Heesbeen WWM, Ruigrok RCJ, Hoekstra J-M. GRACE – a versatile simulator architecture making simulation of multiple complex aircraft simple. Proc. AIAA Modeling and Simulation Technologies Conference and Exhibit, 21–24 August 2006, Keystone, CO, USA, 2006

[5] Hering, A., S. Sénési, P. Ambrosetti, and I. Bernard-Bouissières. Nowcasting thunderstorms in complex cases using radar data. *WMO Symposium on Nowcasting and Very Short Range Forecasting*, Toulouse, France, 2005.

[6] Mirza, A. K., C. Pagé, S. Geindre: FLYSAFE – an approach to safety – using GML/XML objects to define hazardous volumes of aviation space. AMS 13th Conference on Aviation, Range, and Aerospace Meteorology, New Orleans (USA), 20-24 January 2008

[7] Pradier-Vabre, S., C. Forster, W. W. M. Heesbeen, C. Pagé, S. Sénési, A. Tafferner, I. Bernard-Bouissiéres, O. Caumont, A. Drouin, V. Ducrocq, Y. Guillou, P. Josse: Description of convective-scale numerical weather simulation use in a flight simulator within the Flysafe project. Meteorol. Atmos Phys, DOI 10.1007/s00703-008-0317-4, 2008

[8] Rhoda, D.A., et al. Aircraft Encounters with Thunderstorms in En-route vs. Terminal Airspace above Memphis, Tennessee. *Tenth Conference on Aviation, Range, and Aerospace Meteorology*, AMS, Portland, Oregon, May 13-16, 2002.

[9] Tafferner, A., C. Forster, S. Sénési, Y. Guillou, P. Tabary, P. Laroche, A. Delannoy, B. Lunnon, D. Turb, T. Hauf, D. Markovic: Nowcasting Thunderstorm Hazards for Flight Operations: The CB WIMS Approach in FLYSAFE. ICAS2008 Conference, International Council of the Aeronautical Sciences Conf. Proc. (8.6.2), Optimage Ltd., Edinburgh, UK, S. 1 - 10, Anchorge, AK (USA), ISBN 0-9533991-9-2, 2008

[10] Zinner, T., H. Mannstein, A. Tafferner: Cb-TRAM: Tracking and monitoring severe convection from onset over rapid development to mature phase using multi-channel Meteosat-8 SEVIRI data. Meteorology and Atmospheric Physics, 101, S. 191 - 210, DOI: 10.1007/s00703-008-0290-y, 2008

AUTHOR BIOGRAPHY

Arnold Tafferner, meteorologist, got his doctoral degree in 1988 in natural sciences after a one year stay at the Rosenstiel School of Marine and Atmospheric Science in Miami (USA). Holding a research position at the Meteorological Institute at the University of Munich, he specialized in forecasting weather on continental as well as regional scale and in nowcasting severe weather events by use of remote sensing applications. Since 12 years he is employed at the Institut für Physik der Atmosphäre of the Deutsches Zentrum für Luft- und Raumfahrt in Oberpfaffenhofen, Germany (German Aerospace Centre), where he designed and operationally installed systems for detection and forecasting atmospheric conditions which pose hazards to aircraft, e.g. aircraft icing, wake vortices and thunderstorms. His main interests are the fusion of data from various observation systems, including satellite and radar as well as from numerical forecasting, with particular emphasis on nowcasting severe weather for air traffic.

Caroline Forster got her PhD in meteorology at the University of Munich in 2000. Until 2004 she held a position of a post-doctoral scientific research assistant at the Institute of Ecoclimatology of the Department of Ecology at the Technical University of Munich. Thereafter, she was Senior Scientist at the Norwegian Institute for Air Research (NILU, Oslo) until 2006 and since then a scientist at DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany. Her main interests are tracking, monitoring and nowcasting of thunderstorms using remote sensing data and the development of integrated weather forecast systems for air traffic using observations and numerical model forecast data.

Stéphane Sénési is graduated from Ecole Polytechnique, Paris, France (1980) and as meteorologist engineer from the Ecole Nationale de la Météorologie, Toulouse, France (1982). He lead Météo-France's IT development until 1986 and then conducted research and development in nowcasting first with Météo-France's research center (CNRM), until 2001, when he took the lead of the R&D Nowcasting Division of Météo-France Forecast Department in Toulouse, France. Mr Sénési current research interests lie with nowcasting rain and deep convection, and in the man/machine cooperation for nowcasting tasks.

Yann Guillou is graduated from the french navy officer school, Ecole Navale , Lanveoc, France (1995) and as meteorologist engineer from the Ecole Nationale de la Météorologie, Toulouse, France (2001). After ten years as anti_submarine warfare officer, he has rejoined the nowcasting team of Meteo-France in Toulouse. He is development manager of deep convection nowcasting team. He is the local manager of the Rapid development Thunderstorm product of SAFNWC (Satellite Applications Facility on support to Nowcasting and very short range forecasting)